Experimental search for
a new vector boson $A'$

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for R. Essig, P. Schuster, N. Toro and APEX collaboration
The processes which could have U/A’-boson


\[ g_{e-2}, g_{\mu-2} \]
\[ \pi, \eta \text{ decays to } U\gamma \]
\[ \pi, \varphi, \psi \text{ decays to } \gamma + \text{invisible} \]

If the \( U \) boson mainly decays into dark matter, then the \( U \) production process turns out to be of the type \( e^+e^- \rightarrow \gamma + \not{E} \), where \( \not{E} \) is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate, such a process is likely to remain unobserved, owing to the large background associated with \( e^+e^- \rightarrow \gamma\gamma \), in which one of the two photons escapes detection.

Upper limit for the coupling constant
\[ |f_{eU}|^2 < 2 \times 10^{-8} (m_U)^2 \]

A.6.1. Direct \( U \) boson production
Physics motivation

Why?

Search for new forces mediated by $\sim 100$ MeV vector boson $A'$ with weak coupling to electrons

$$\alpha' \equiv \frac{f^2}{4\pi}$$

Significant new reach in $\alpha'$ ($\sim$2-3 orders of magnitude)
Broad interest in particle physics community

- new gauge force
- dark matter interactions?
- $(g-2)_\mu$ and HyperCP anomalies
Physics motivation

Weak $A'$ couplings are generic (generated as quantum corrections if any heavy particle interacts with $\gamma$ and $A'$) [Holdom]

\[ \Delta L = \frac{\epsilon}{2} F_{Y,\mu\nu} F_{\mu\nu}' \]

"kinetic mixing"

In simple models: $m_{A'}^2 \sim \epsilon M_W^2 \sim \text{MeV}^2 - \text{GeV}^2$
Physics motivation
Dark Matter Anomalies – one source?

1) No antiproton excess observed!
   – not consistent with annihilation into $g \cdot W^{\pm} Z$
   $\Rightarrow$ new force?
   – suggests $m_{A'} \lesssim 1$ GeV
   $\Rightarrow$ decay to protons is
   kinematically forbidden,
   $A' \rightarrow \ell^+ \ell^-, \pi^+ \pi^-$

2) Observed annihilation rate is large!
   – consistency with standard cosmology requires attractive force with
   range $\gg 1/m_{DM}$ $\Rightarrow$ again suggests $m_{A'} \lesssim 1$ GeV

Irrespective of anomalies: New $\sim$GeV–scale force carriers are
important category of physics beyond the Standard Model.
Fixed-target experiments have unique capability to explore this vast territory!
Existing limits and **APEX Sensitivity**

Direct production: $e^+e^- \rightarrow \gamma A'$

**Gray regions:** excluded (2$\sigma$) by past experiments

**Dashed lines:** estimated 2$\sigma$ sensitivity of other possible searches in existing KLOE, KTeV, and Belle data.

No past experiment has **sufficient statistics and mass resolution** to see $A'$ if its coupling is below the dotted lines.

This is a theoretically motivated region

– relevant for dark matter

– predicted by grand unification
A’ Properties in APEX Search Region \((\alpha'/\alpha > 10^{-7})\)

- Produced abundantly through bremsstrahlung (e.g. >1/second for 75 μA beam, 0.1 \(X_0\))

  ![Diagram showing electron and positron production](image)

- A’ decays promptly to \(e^+e^-, \mu^+\mu^-,\) or \(\pi^+\pi^-\)
  \[\Rightarrow\text{large QED background}\]

**Strategy:** measure \(e^+e^-\) mass spectrum precisely, in kinematic region optimized for A’ acceptance and QED background suppression
Approach: $A'$ Production and Background Kinematics

Production diagrams analogous to photon bremsstrahlung

QED Backgrounds

$N \sim \alpha' \times \text{branching} \Rightarrow O(1)$

(rates before angular cuts)

$A'$ products carry full beam energy!

- Distinctive kinematics
- Assists in background suppression

Best kinematics to select events for $A'$ search
Narrow Resonance Search

To identify $A'$ signal, must study invariant mass distribution

$$m_{A'} \approx \sqrt{E_+ E_- (\theta_+ + \theta_-)}$$

In mass window $\Delta m$:

$$\frac{S}{\sqrt{B}} \propto \frac{\alpha'}{\alpha} \sqrt{N_{QED} \left( \frac{m_{A'}}{\Delta m} \right)}$$

To search at small $\alpha'$, need:

- ★ High $e^+e^-$ statistics
- ★ Excellent mass resolution is a key
CEBAF Accelerator

Re-circulating linac design
Up to 5 pass, 0.3 to 1.2 GeV per pass.
6.0 GeV max beam energy
100% duty cycle
2ns microstructure
$\sigma_E/E < 1 \cdot 10^{-4}$ (Halls A & C)
Beam polarization up to 85%
180 $\mu$A max current
Hall A at Jefferson Lab

Beanline
$\sigma_{E/E} < 2 \cdot 10^{-4}$ (absolute)
Non-invasive 3% polarization measurement

Two High Resolution Spectrometers originally designed for $(e,e'p)$ expts.
Hall A at Jefferson Lab

Two HRS Spectrometers
0.3 < p < 4.0 GeV/c
-4.5% < Δp/p < 4.5%
6 msr at 12.5° <θ<150°
4.5 msr at θ=6° with septum
-5cm<Δy<5cm

Optics: (FWHM)
δp/p ≤ 2·10^{-4} (achieved)
δθ=0.5 mrad, δϕ=1 mrad
δy=1mm

Luminosity ~ 10^{38} cm^{-2}s^{-1}
High Resolution Spectrometer

HRS Design Layout
(designed magnet effective lengths displayed)

Dimensions in meters

1 m

Q1

Q2

Q3

1st VDC Plane

10.37

20.76

4.42

1.69

1.25

1.80

0.80

8.40

3.57

3.05

1.80

45°

30°

30°
Test Run: June 2010

\[ E_{\text{beam}} = 2.262 \text{ GeV}, \ \text{Ta target of 15 mg/cm}^2 \]

- Signal dominated at \( E_+ = E_- = E_{\text{beam}}/2 \)
- Use septa to achieve 5° central angles
Test Run: June 2010

Run #1780 Tantalum target with 56 uA Coincidence trigger events

- Events vs. TDC Channels, 0.5 ns
- Positron Arm $f_{scin} = 765$ kHz

Run #2047 Tantalum target with 12 Coincidence trigger events

- $E^+ vs. E^-$
- $E^+ + E^-$

Tantalum Coincidence Peak

e+ momentum versus e- momentum

momentum sum of coincident e+e

16
Test Run Results

The $e^+e^-$ mass distribution

Final Coincidence Sample

Search for a narrow signal
Test Run Results

APEX test run found no evidence for $A'$ in the mass range 175-250 MeV with the coupling above $\sim 10^{-6}$
Options for $e^+e^-$ experiment at low $s$

A “very” low energy $s^{1/2} \sim 10$–30 MeV

a) Search in existing data from good detector => difficult to get resolution at low $s$

b) 5 MeV x 5 MeV head-head collider of $e^+e^-$ => problem of very low luminosity

c) Sliding beams of $e^+e^-$ (200 MeV x 200 MeV) => needs specialized accelerator with two rings

d) Solution is: positron beam and atomic electrons

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A.6.1. Direct $U$ boson production

\[ e^+ \rightarrow e \rightarrow e^+ + \gamma \]

\[ e^- \rightarrow U \rightarrow e^- + \gamma \]
Positron beam on internal Hydrogen target

Experiment layout at VEPP-3 (Nikolenko, Rachek, BW)
Positron beam on internal Hydrogen target

\[ \sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1) \]

\[ N_{U\gamma} = 2\frac{\alpha'}{\alpha} \cdot N_{\gamma\gamma} \]
Positron beam on internal Hydrogen target